AN EXAMINATION OF THE PERMO-TRIASSIC RESERVOIRS OF THE PRUDHOE BAY FIELD NORTH SLOPE, ALASKA

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III. ABSTRACT

Production from the Prudhoe Bayfield, which contains the largest accumulation of oil ever discovered in North America, commenced in 1977. While the spectacular construction of the Trans-Alaska Pipeline was taking place, the drilling and production crews worked at an incredible pace to prepare the field to supply the pipeline's estimated 1.5 million b/d capacity.

During the past 10 years of operations a considerable amount of subsurface data has been collected on the Permo-Triassic reservoirs. These reservoirs are contained in the following formations, in decending order, the Sag River Formation, the Shublik Formation, and the Ivishak Sandstone. Most of the fields' hydrocarbons are contained in the Ivishak Sandstone reservoir of the Sadlerochit Group.

Through the availability of these subsurface data, this paper describes the geological and petro-physical aspects of the main Prudhoe Bay reservoirs.

IV. INTRODUCTION

A historical review of the geological and geophysical exploration in northern Alaska exemplifies the lead time and growth of knowledge that is necessary for the discovery of such a great oil field as Prudhoe Bay. The North Slope history also summarizes what has or has not been evaluated and where further exploration should be pursued in the Artic region.

Long before recorded history, the Eskimos had known of oil and gas seepages and combustible oil shales in northern Alaska . These include oil seepages at Skull Cliff, Cape Simpson, Fish Creek, Barter Islands, and Umiat. The central Colville River region contains the only known gas seepages (fig. 1). The first description of oil seepages by E. de K. Leffingwell was sent to the USGS in 1906 and published in Brook's report in 1909.

In 1901 Peters and Schrader made the first recorded geological expedition to the North Slope and published their results in 1904 in USGS Professional Paper 20. This extensive expedition went over land to the Koyukuk River, up the Koyukuk and John Rivers to Anaktuvuk Pass, through the pass and along the coast by canoe to Cape Lisburne. Shrader studied the broad anticlinal structures in the Cretaceous rocks and described in great detail the Lisburne Formation of Mississippian age.

E. de K. Leffingwell mapped the Artic Coast east of Barrow and traveled inland in the Canning River region. In his report, Professional Paper 109 published in 1919, he described and named the now-famous oil bearing Sadlerochit Sandstone, and his paper is an excellent reference, especially on the subject of permafrost.

The oil industry became interested in the Artic Coast in 1917, because of "Sandy" Smith's research on oil seepages. In 1921, many companies filed applications for prospecting permits on claims near Peard Bay, Cape Simpson, and along the Kukpowruk, Kokolik and Meade Rivers. Yet the remote artic region was forgotten when large amounts of oil were discovered in Texas and Oklahoma.

As future petroleum needs became apparent, the U.S. Navy's National Petroleum Reserve No. 4 (NPR-4) was established by Executive Order in 1923, to provide for possible U.S. Navy needs. The Navy recognized that adequate geologic and geographic information was needed to properly administrate the reserve. The USGS was asked to obtain this information on the NPR-4 area. From 1923 through 1926 USGS expeditions traversed the Brooks Range and mapped the geology and geography on reconnaissance scales. The results of this work were published by Smith and Mertie in USGS Bulletin 815 in 1930.[1]

Smith and Mertie studied the petroleum possibilities of the region and described several rock units in northern Alaska. They believed that the apparently widespread oil shales contained the best possible petroleum sources. Smith and Mertie recognized no abundant source rocks in the Cretaceous strata, but felt that Paleozoic source rocks were extremely problematic. They had studied several anticlinal structures but evaluated them to be small and economically unfeasible when the harsh Artic environment is considered. They described the major structure north of the Brooks Range as a regional dip or monocline to the north. They concluded that the next step in evaluating northern Alaska should be the drilling of an exploration well in the vicinity of Cape Simpson to determine the stratigraphy and structure, followed by field studies in potential areas.

The NPR-4 drilling program explored the area from 1945 through 1952, 36 test wells and 45 shallow core tests were drilled. During this period they found one large oil field, Umait; one large gas field, Gubik; one small gas field, Barrow; three prospective gas fields, Wolf Creek, Square Lake, and Meade; and two minor oil deposits at Fish Creek and Simpson. This program developed many new techniques in Artic exploration and estimated the feasibility of conducting a modern program in the northern Alaska region.[2]

In 1952 the NPR-4 program was completed and no new wells were drilled until 1963. Between 1963 and 1965 British Petroleum and other companies drilled seven shallow test wells near Umiat. Then in 1966 ARCO drilled Suise No. 1 and two test wells near the Colville delta, which were completed as dry but had shows of oil. In 1968, the ARCO-Humble Prudhoe Bay State No. 1 discovered oil (fig. 2).

The USGS has continued its stratigraphic and geologic studies of northern Alaska to provide oil companies with important geological information. As a result of this work the majority of the Brooks Range and the Artic Coast has been mapped. The regional geology is shown in figure 3, and shows the Brooks Range as a belt of Peleozoic rocks in flat and imbricate thrust relations. The narrow disturbed belt borders the northern edge of the Brooks Range and represents the northward thrusting of Paleozoic rocks and Early Cretaceous orogenic deposits.

The Cretaceous Colville geosyncline is north of the disturbed belt and is divided by the Meade Arch into the Umiat and Chukchi basins. The two major anticlinal structures show a continuous nature, the southerly one, the Carbon Creek-Ayiyak structure can be traced for more than two hundred miles. The northern structure is the Umait-Oumalik-Meade trend and may represent the northern limit of the Cretaceous decollemont. The Cretaceous basin is disrupted by thrust to the south, and deopens to more than 20,000 ft. (6096 m) in the vicinity of Uniat and gradually rises to 2,500 ft. (762 m) in the Barrow Arch area, then deepens to approximately 3,000 ft. (2,438 m) in the Colville delta area.

The mid trough pre-Cretaceous basement still remains to be explored. In the area of the Romanzof Uplift, and on the Barrow arch, Jurassic and (or) Cretaceous rocks overlie Triassic, Carboniferous, and Devonian strata in sequence. These rocks lie unconformably on schist and phyllites.

The eastern and central stratigraphic sequence is shown in figure 4. The stars indicate formations where oil and gas has been discovered. Starting at the top they are the Gubik gas field in the Prince Creek Formation, the Square Lake gas field in the Seabee Formation, both in the Upper Cretaceous Colville Group, the Gubik and Umiat fields, within the upper Ninuluk Formation, the Umiat and Meade gas horizons in the Kukpowruk and Grandstand Formations of the Nanushuk Group, and the Barrow gas "sands" of Jurassic age. The most recent discoveries include the Kuparuk River sands of Early Cretaceous age, the Permo-Triassic "sands" of the Sag River, Shublik, and Sadlerochit Formations, which are the topic of this paper, and the carbonate reservoir horizons of the Lisburne Group.

V. PERMO-TRIASSIC STRATIGRAPHY

The most important accumulations of hydro carbons in the Prudhoe Bay field are contained in Permo-Triassic reservoirs. The Permo-Triassic is divided into three formations, in decending order they are the Sag River, Shublik, and the Sadlerochit formations. The thickest of the three reservoirs is the Ivishak Sandstone of the Sadlerochip Group which has an oil column of 450 ft. (137 m). The published reserves of the field are 9.6 billion bbl of oil and 26 Tcf of gas. The whole Permo-Triassic section with its northeastward thinning is illustrated in figure 5. Its base lies unconformably on the eroded surface of the Lisburne Group and its upper limit is transitional with the overlying Kingak shales of Jurassic age (fig. 6).

A. Sadlerochit Group

In the Prudhoe Bay area the Sadlerochit Group consists of three distinct lithologic types: a lower glauconitic sandstone section, a middle shale and mudstone section and an upper sequence of conglomerates, sandstones, and mudstones (fig. 7). The reference section for the Sadlerochit Group is BP well 19-10-15, since the whole sequence has been covered with one logging run (fig. 8). The group is divided into three formations.

1. Echooka Formation

The Echooka Formation is defined as the interval 9,729 - 9,780 ft. (2965-2981 m) - electric log depths-in well BP 19-10-15 (fig. 8). Within the south west portion of the field the Echooka Formation is approximately 70 ft. (21 m) thick and thins to zero north of an east-west line through the center of the field (fig. 9C). The formation onlaps the eroded surface of the Lisburne Group and was probably deposited in a shallow, northward transgressing sea (fig. 10).

It has a poor microfloral assemblage and is roughly dated as mid-Permian on the basis of polynomorphs. The presence of multistriate pollen especially Vittatina, and the absende of Lueckisparites virkkiae support the mid-Permaian age. The latter, a distinct Late Permian species, occurs in the overlying Kavik Shale.

The Echooka Formation lithology consists of green and dark gray sandstones with thin laminae and stringers of clay and shale. The sandstones are fine grained, argillaceous, glauconitic, phosphatic, and pyritic, and they contain small amounts of siderite and dolomite. The formation does not seem to be an attractive reservoir in the Prudhoe Bay field because of its shallow-water, high-energy depositional environment, with the argillaceous stringers having been deposited at low tide.

2. Kavik Shale Formation

The Kavik Shale is present in every well that has been drilled to the Lisburne Group. It is defined as the section between 9,513 - 9,729 ft. (2,809 - 2,965 m) - electric log depths -

in well BP 19-10-15 (fig. 8). In the field area, the formation thins from 230 ft. (70 m) in the south to approximately 100 ft. (30 m) near the coast. The greatest thinning occurs north of the pinch out of the Echooka Formation where the Kavik Shale onlaps the eroded surface of the Lisburne Group (fig. 9B). The Kavik Shale conformably overlies the Echooka Formation in the south and is gradational with the overlying Ivishak Sandstone. Its depositional environment was probably a shallow sea that transgressed northward over the eroded surface of the Lisburne Group. This northward transgression was reversed some time during its deposition and a southward regression was begun.

The Kavik Shale Formation has been dated as Late Permian with the dating based on the occurance of Lueckisporite virkkiac and an abundance of multistriate pollen, particularly Striatoabietites richteri.

The formation contains a few small reservoirs, which consist of thin, silty, sandstone lenses. The formation is mainly composed of fairly uniform, medium to dark gray, silty shales, which are non-calcareous, pyritic, and micaceous.

3. Ivishak Sandstone Formation

The Ivishak Sandstone is defined as those strata occurring within the interval 8,936 - 9,513 ft. (2723 - 2,899 m) - electril log depths - in well BP 19-10-15 (fig. 8). This formation contains the major hydrocarbon reservoirs in the Prudhoe Bay field.

The Ivishak Sandstone is composed of shallow marine deltaic and fluvial deposits that formed during the southward regression. The base of the formation varies since the Kavik Shale grades into the Ivishak Sandstone. The top of the formation is clearly designated by both a thin phosphatic, radioactive conglomerate and a highly pyritic sandstone. The highly radioactive streak is clearly indicated by resistivity and gamma ray logs making the formation top easily recognizable (fig. 11). The Shublik-Sadlerochit contact is probably unconformable, at least in the northeastern portion of the field, since the Ivishak Sandstone thins at the top instead of at the base of the formation and also the presence of the pyritic and radioactive conglomerate intervals. Further west, in the Eileen area, the contact is gradational and the pyritic and radioactive intervals are less apparent.

The Eileen zone consists of slightly calcareous sandstones and shales and occurs between the "typical" Shublik as recognized in the Main area and the Ivishak Sandstone (fig. 8). This interval is less arenaceous than the Ivishak Sandstone and less calcareous than the Shublik Formation, and marks the gradational transition between the depositional environments of these two formations.

The Ivishak Sandstone contains few macrofauna or microfauna, although several microfloral assemblages have been recognized.

Striatoabietts richteri is the most abundant pollen type, but other multistriate species such as Lunatisporites, Protohaploxypinus, Striatopodocrapites, and Strotersporites have been identified. The important nonsaccate gnetalean type, Gentaceaepollenites steevesi have been recognized, which is typical of the Middle to Late Permian and the Early Triassic of the northern hemisphere. The upper portion of the formation lacks the distinctive Late Permian species Lueckisporites rirkkiae which correlates with the Kavik Shale. However, no species have been identified that are younger than Early Triassic. Therefore, giving the Ivishak Sandstone a tentative date of Late Permian to Early Triassic.

The formation thickness ranges from approximately 300 ft. (90 m) in the northeast to 600 ft. (200 m) in the south (fig. 9C). The pre-Shublik erosion is probably the cause of the thinning at the top of the Ivishak Sandstone.

The subdivisions of the Ivishak Sandstone are shown in fig. 12. The subdivisions are an informal system that was devised to facilitate the reservoir description. The formation has been divided into five members, lettered A through E from the base upward, so the system could accommodate the future discovery of members under the possible pre Shublik unconformity.

a. Member A

This is the lowest member, consisting of horizonally bedded siltstones, sandstones, and mudstones. They represent the initial influx of prodelta, coarser sediments into the southward regressing sea and are described as a "stream-mouth bar sequence".[3] The member is further subdivided into two sub members. Submember A_1 is the more silty and shaly and generally older deposit, that mainly occurs to the southwest. Submember A_2, is cleaner and coarser and is located in the northwest.

Submember A_1 thins northeastward as it is laterally replaced by the upper submember A_2. Submember A_1 thins from 140 ft. (43 m) in the west and is absent in the northeast. Conversely A_2 thins from 80 ft. (24 m) in the north and disappears along the southwest margin of the field. The total thickness of the member ranges from 60 to 140 ft. (18 - 43 m). The top of a mudstone that has been correlated throughout the field is used to mark the top of the member.

Members B, C, D compose the conglomeratic section of the formation and were deposited as part of a delta and braided stream environment. The number of mudstones decreases and the conglomerate content increases stratigraphically upward and laterally northward.

b. Member B

This member has been separated from the rest of the conglomeratic section since it contains the most mudstones, especially to the southeast and west. The member also contains sandstones, conglomeratic sandstones and conglomerates that generally have high sedimentary dips and eroded bed contacts. The increase in sedimentary dip upwards, suggests a gradual change to a fluvial or distributary enviroment. Member B is 100 - 140 ft. (30 - 43 m) thick and thins towards the south and north. The top of the member is marked by a correlatable mudstone

Members C & D are easily recognized on gamma-ray logs, because they form a distinct "plateau" [4] of low radioactivity caused by the absence of mudstones and the small amounts of argillaceous matrix in the sandstones and conglomerates.

c. Member C

This member has a higher porosity and fewer mudstones than member B and less conglomerates than member D. There is not a distinct lithology change at the top of the member and it is arbitarily selected where the sonic log interval transit time decreases below 85 micro seconds in an upward direction.

Member C is thickest in the south, greater than 169 ft. (49 m), and thins northward as its upper portion becomes replaced by the less porus conglomerates of member D.

d. Member D

This member consists of conglomerates and conglomeratic sandstones with its top being taken at the top of a thin interval of mudstones. To the east, the upper part of the member changes laterally into interbedded mudstone and sandstone facies and finally is replaced by mudstone.

In the central area of the field Member D contains numerous pyritic intervals giving rise to false positive deflections on the SP curve which can be misinterpreted as mudstone or a non productive layer if not supplemented by core data and gamma ray logs. Member D thins to the southeast, south, and southwest from a maximum thickness of 140 ft. (43 m).

e. Member E

The uppermost member of the formation consists of homogenous sandstones and thin mudstones. The lower portion probably represents a fluvial enviroment as it contains a series of finning upward beds and was succeeded by a near shore beach enviroment. In the southwest Member E is over 200 ft. (61 m) thick and thins somewhat regularly towards the northeast where it eventually pinches out. This thinning could be due to subsequent erosion or original depositional thinning.

Member E is composed of arenaceous chert and quartz deposits. The conglomerates contain pebbles of argillite, this conglomerate forms the basement rock in the North Slope area. It is believed that both the Lisburne and basement rocks were exposed and eroded to form the source of the Ivishak Standstone, with pyrite and siderite as common secondary minerals.

The sandstone to shale ratio for the Ivishak Sandstone is shown in figure 13 and indicates that the ratio of shales, or more correctly mudstones and siltstones, increases away from the apparent source area to the north. It shows a fan or delta shaped accumulation of sediments, with sandstones increasing stratigraphically upward. In general, pebble and grain size increase upward and northward.

This data has led to the following paleographic interpretation for the area. The Echooka Formation was deposited during a period of transgression with gradual rates of subsidence and sediment accumulation. Regression began during deposition of the Kavik Shale and continued until Member D of the Ivishak Sandstone was deposited. During this period the rate of sediment supply increased as a result of more rapid uplift of the source areas and consequently greated stream velocities, thus building a wedge of sediments father to the south. The paleogeography during deposition of each member of the Ivishak Sandstone is shown in figure 14. Members A through D probably represent the transition from prodelta through delta to distributary channels to meandering high energy rivers. Member E may represent a period when the source area was almost denuded of sediments, when stream velocities decreased and when the earlier deposits were worked by a near shore enviroment. This change in enviroment is though to be fairly abrupt since the division between Members D and E is very distinct.

The Ivishak Sandstone is a major reservoir for two reasons; its great thickness and a real extent and its excellent petrophysical properties.

The sandstones and conglomerates are generally poorly cemented, contain little matrix, are laterally continuous, and are not separated by numerous thick mudstone intervals, also the average sandstone/shale ratio within the reservoir is greater than .9 (fig. 13). During deposition, stream or current action has winnowed and reworked the sandstones and conglomerates making the sediments clean with verylittle matrix. In general the finer grained sandstones of Member A and the poorly sorted, pebbly Member B contain the poorer reservoirs.

The three major reservoir characteristics, porosity, permeability and lack of interbedded mudstones, all improve laterally north to northeastward as well as stratigraphically upward. Porosity varies greatly within each member but each member increases northward, and the average is approximately 30%. Permeabilities average 1 millidarcy for some members and when averaged from core data they tend to increase northward toward the source. The sandstone/shale or net/gross sandstone ratio for each member follows the general trend for the entire formation. The ratios of Members A and B vary, and represent a decrease in the number of argillaceous beds northward and upward. Members C and D contain very little mudstones, the mudstones in Member E are thin and have very limited lateral extent.

B. Shublik Formation

In 1919 E. de K. Leffingwell identified the type locality for the Shublik Formation as the exposure on Shublik Island in the Canning River. To the east, the formation is exposed at Fire Creek and the typical section of the Shublik Formation in the Prudhoe Bay area is seen in well BP 19-10-15 (fig. 11), at an interval of 8,866 - 8,935 ft. (2,702 - 2,723 m) electric log depths.

The Shublik Formation is composed of bioclastic arigillaceous and pelleted limestones, slightly calcareous sandstones, mudstones, and phosphatic beds. In the Prudhoe Bay field, the formation can be divided into five members, based on core and log data. The members have been labeled A through E from the top (fig. 16 & 17). Since there was a possibility that other members might have been described beneath Member E.

a. Member E

This member is located between 8,913 - 8,935 ft. (2,722 - 2,723 m) electric log depths in well BP 19-10-15 (fig. 11). The member is distinguished on the gamma ray log at the interval between the radioactive peak that located the Sadlerochit Group and the peak at the base of Member D. Its lithology varies from a mudstone/siltstone in the Mainfield area to a sequence of interbedded, slightly calcareous sandstones, siltstones, and mudstones in the Eileen area.

b. Member D

This member is present between 8908 - 8913 ft. (2715 - 2722 m) electric log depths in well BP 19-10=15 (fig. 11.) This member contains "tight" argillaceous limestones interbedded with calcareous mudstones and shales. It is characterized by high resistivities, low sonic transit times, and low radio activity. The top is taken as the lower limit of a zone of high radioactivity.

c. Member C

This member is located at the interal 8,888 - 8,908 ft.

(2,709 - 2,715 m) electric log depths in well BP 19-10-15 (fig. 11). This member contains a complex lithology ranging from bioclastic, pelleted, and rubly limestones to siltstones and shales, it is highly glauconitic and phosphatic. The member is highly radioactive,which produces an easily correlatable resistivity low.

d. Member B

This member is picked at the interval 8,880 - 8,888 ft. (2,707 - 2,709 m) electric log depths in well BP 19-10-15 (fig. 11). This member is composed of shales and mudstones, locally interbedded with bioclastic limestones, siltstones and beds which contain pelleted phosphate. The top of the member is marked by a resistivity low that can be correlated across the field.

e. Member A

The uppermost member is taken as the interval 8,866 - 8,880 ft. (2,702 - 2,706 m) electric log depths in well BP 19-10-15 (fig. 11). It contains a changing lithology within the field area, ranging from bioclastic, sandy limestones through calcareous siltstones to calcareous shales and silty mudstones. On the electric log the member shows as a resistivity interval. The top is arbitrarily taken at the base of the Sag River Formation. Both Members A and B appear to become increasingly arenaceous towards the northeast and the upper boundary is indistinguishable without the use of a gamma ray log.

The Shublik resembles a shelf margin enviroment with low energy and moderate water depths of between 200 - 1000 ft (60 - 305 m). The highly phosphatic beds suggest slow deposition and reworking of sediments. Coquina beds were formed by the diverse fauna of marine invertebrates. The presence of large vertebrates has been noted in some cores.

In the Main field area the Shublik Formation thickens from 80 ft. in the west to 50 ft. in the east (fig. 15). The thickness increases greatly to the west reaching a maximum of 192 ft. (59 m) in well 29 - 12 - 11. Although all of the members thicken westward, the thickest is Member E.

Member C and E seem to contain the only potential reservoirs in the Shublik Formation. Certain intervals of Member C have porosities of over 30% and permeabilities of up to 400 md. These intervals have been described as sandy, pelleted, and rubly limestones; crumbly and porus calcarenites and porous coquina.

It has been postulated that the sporadic occurrence of high sonic log readings represents the possibility of only locally high porosities. The eratic porositiy distribution may be related to slumping and faulting that occurred soon after deposition causing brecciation of the partially consolidated sediments.

Member E has porosities that range from 5 to 15%, but low permeablities. It has formed a small reservoir in the Eileen area where it is interbedded with sandstones and mudstones.

C. Sag River Formation

In the Prudhoe Bay field, the Sag River Formation occurs within the interval 8,555 - 8,591 ft. (2,607 - 2,618 m) electric log depth in well BP 21-11-13 (fig. 16). The top of the formation is marked by an increase in resistivity which represents a downward increase in silt content in comparison to overlying Kingak Shale. The formation base is defined on the basis of; a decrease in the proportion of sandstone, an increase in calcareous content, and the common presence of a thin bed of shell hash. Also resistivity values are at a minimum and the gamma ray log marks the base with a peak of high radioactivity.

The sandstone member is indicated as the horizon between 8560 - 8591 ft. (2,609 - 2,618 m) electric log depths in well BP 21-11-13 (fig. 16). This interval is between the two radioactive peaks which mark the base of the "shale member" and the base of the Sag River Formation. This boundary can further be defined by the high proportion of glauconite at these radioactive peaks.

The sandstone member consists of a uniform, well-sorted, fine-grained sandstone to siltstone. It is composed mainly of quartz with variable amounts of chert and glauconite. The most common cement is dolomite with clay matrix occurring as both thin sheaths around the clastic grains or descrete laminae of brown hematitic clay. The clay laminae are broken and disrupted possibly due to bioturbation. Pyrite occurs both as fine dust and clusters of cubic crystals. The rock color is light greenish-gray with the intensity of green proportional to the percentage of glauconite. The sandstone member appears to have no bedding planes.

The sandstone member may represent a barrier beach enviroment which progrades over the shallow marine Shublik formation. The glauconitic, fossiliferous, and radioactive siltstones within the base of the formation and sporadically within the upper part of the Shublik Formation may indicate time planes and a period of slow undisturbed deposition.

The shale member-correlates with the interval 8,555 - 8,560 ft. (2,607 - 2,609 m) electric log depths in well BP 21-11-13 (fig. 16). The gamma ray log correlated with the upper most of the two radioactive peaks and marks the base of the member.

The shale member is composed of medium-grained, dark/gray to black, glauconitic, and pyritic shales mudstones with thin laminae of silt. In the field area the member is approximately 10 ft. (3 m) thick yet it thickens westward to 70 ft. (21 m) in the Topagoruk No. 1. The shale member of the Sag River Formation lies within the unclear Triassic-Jurassic boundary. Since no direct paleontological dating is available within this interval, the boundary is arbitraryily set.

All of the Sag River Formation reservoirs are contained in the sandstone member. The sandstone consists of a continuous interval, which is less than soft (6 m) in the south, and thickens to 70 ft. (21 m) in the north (fig. 15A). The nonreservoir interval is located near the top of the formation. Net sandstone thickness changes from 15 ft. (4.6 m) in the south to over 60 ft. (18 m) in the north. The lower part of the reservoir rock, south and west of the field, becomes more silty and finer-grained than the upper portion. Reservoir characteristics increase northward; average porosity increases from 10 to 25%, and permeabilities increase to approximately 70 md. Bioturbation tends to be common in rock descriptions where porosities and permeabilities are greatest, thus supporting the theory that bioturbation is associated with the improved reservoir character.

VI. STRUCTURE OF THE BARROW ARCH

The northern flank of the Colville Basin and the Barrow Arch is a stable shelf area that dips less than 2^{o}, except in fault areas. The northern flank of the arch has a slightly steeper dip than the southern flank. Seismic sections, along the gently dipping southern flank, indicate beds of uniform thickness slowly converging towards the north. The faults on the Barrow Arch are all of normal type. Only the Lower Sequence of beds, defined as those beds of Mississippian to Lower Cretaceous age, are displaced by the faults. In most cases the Upper Sequence, ranging in age from Lower Cretaceous to Tertiary, shows no movement after deposition and when the beds are displaced the distance is very small. The displacement due to faulting of the beds in the Lower Sequence does not change the thickness of the beds. This information suggests that there was one major period of faulting during the Upper Neocomian to Barremian ages. This same period, at approximately the Jurassic-Cretaceous boundary, marks the beginning of the rise of the Brooks Range. This large series of earth movements changed the entire northern Alaska depositional regime.

Through examination of the Lower Sequence of sediments, it has been noted that a large portion of the area now occupied by the Arctic Ocean was once an area of continental rocks. The proposed theory suggests that during the deposition of the Lower Sequence, the northern Alaskan coast was connected to the northern edge of the Canadian Sheild. During the Lower Cretaceous earth movements, Alaska separated from Canada by a pivoting motion. If this hypothesis is correct, then the Lower Sequence at Point Barrow would be opposite Prince Patrick Island and the Prudhoe Bay field would be adjacent to the southern portion of Brooks Island, Canada. This theory was made popular by Carney (1958) and has been expounded by Mr. Irv Tailleur[5]. This theory has been very influential in location of further exploration, especially in Canada.

The sequence of events in the formation of the Arctic Ocean and the development of the northern continental margin of Alaska are illustrated in figure 17. The first stage shows the sediments of the Lower Sequence being eroded from the Canadian Shield and being deposited in the Colville Basin. This period was before the rise of the Barrow Arch and formed a uniform gently dipping shelf. The second stage illustrates an early episode of rifting in the Arctic Ocean, with the edges of the rift being elevated. This was the time when the Lower Sequence was truncated over the Barrow structure. During rifting, a series of normal tension faults developed with their downthrow towards the forming basin of the Arctic Ocean. As the rift valley formed it acted as a sediment trap and restricted the transportation of sediment from the Canadian Shelf to the Colville Basin. The last diagram represents a later stage in the rifting, when the newly formed northern Alaskan continental margin had begun to sag downwards towards the newly opened Arctic Ocean. This stage of downwarping represents the development of the Barrow Arch. The Barrow Arch marks the line where the beds that once dipped southward begin to dip northward, as a result of the continental sagging of Cretaceous times. Also stage three diagrammatically illustrates the trapping mechanism of the Prudhoe Bay field.

VII. ORIGIN OF HYDROCARBONS

The Permo-Triassic reservoirs were exposed at the surface in early Cretaceous, therefore the emplacement of hydrocarbons into the Prudhoe Bay field must have been after early Cretaceous times. Shales of Barremian age sealed the structure. Two possible sources for the hydrocarbons have been suggested. One possible source is the Lower Sequence which includes those strata lying below the Lower Cretaceous unconformity and the second possibility is the Cretaceous beds themselves.

The Jurassic shales and Cretaceous marine shales have been described as potential sources of hydrocarbons.[6] The two parameters that are used to back Morgridge and Smith's interpretation are the total organic carbon and the C_{15+} hydrocarbon content. The Jurassic shales proved to be high in both indices, and the Cretaceous marine shales contained 3000 ppm C_{15+} hydrocarbons and 5.4 weight-percent of organic matter. Since the Cretaceous marine shales are the only strata in direct contact with all of the fields' reservoirs, they represent the most likely source.

Crude oil samples from the Kuparuk River Formation, the Ivishak sandstone and the Upper Cretaceous sandstones have been tested using a variety of geochemical indices including; n-alkane variations, acyclic isoprenoid alkane "fingerprint" distributions, porphyrin-type variations, and stable carbon isotope ratios. These tests showed a close similarity between the samples from the Sadlerochit reservoir and those from the Kuparck River sands, which supports the theory that the reservoirs adjacent to the unconformity contains oils that are of common orgin. Although the heavy crudes from the Upper Cretaceous sandstones are different in chemical composition, their stable carbon isotape ratios indicate that their origin was similar to those oils below the unconformity. The stable carbon isotope ratios of the three reservoirs suggest that their oils probably originated in a restricted, marine enviroment with terrestial material making up a major portion of the source material. This coincides with the depositional envirorment of most of the Cretaceous sediments.

This information supports the theory that the Cretaceous shales and mudstones seem to be the most probable source of the hydrocarbons contained in the Permo-Triassic reservoirs.

VIII. MIGRATION OF HYDROCARBONS

The previous section described the evidence that supports the belief that the source of hydrocarbons found in the reservoirs of the Prudhoe Bay field are Cretaceous, and possibly Jurassic, marine shales. It is not known how the oil migrated structurally upward and stratigraphically downward, however the following evidence supports this type of movement.

The reservoirs lie directly under the Jurassic shales, and, along the truncation area, are in direct contact with the Cretaceous shales. Also, the oil may have migrated along a conduit that formed in the plane of the unconformity. The large faults within the field may connect the field with the shales to the north. Stratigraphically downward movement may have been aided by faulting to the south of the field. The oil probably did not migrate from the sandstones to the west of the field since the aquifers lack any residual oil saturation. Another important reason is that all the reservoirs that are truncated by the unconformity are known to contain hydrocarbons. Also any oil generated in rocks underlying Permo-Triassic strata would have escaped during the early Cretaceous erosion. During that time the Lisburne was over 3,000 ft. (914 m) deep and probably had enough overburden and paleothermal history to produce hydrocarbons. In addition the field is located south of the Barrow Arch, which would be the focal point for the migration of any hydrocarbons formed in the deep basin that surrounds the arch to the south, east, and north. The Colville

Trough contains at least 15,000 ft. (4,575 m) of Lower Cretaceous rocks and the Upper Cretaceous strata to the north and east are similar in thickness. If the Cretaceous marine shales could allow movement of hydrocarbons, then these strata are the most probable source of the Prudhoe Bay hydrocarbons.

After the emplacement of the hydrocarbons, the Permo-Triassic reservoirs were tilted. This tilting was discovered when core analyses from below the oil-water contact in the eastern portion of the field contained residual oil saturation. While cores taken below the oil-water contact, in the western part of the Main field area, show no residual oil.

The base of these residual oil saturations was contoured and indicated a surface which dips east-northeast across the field. The presence or absence of residual oil beneath the oil-water contact can be used to divide the field into four areas.

West of the main field is an area in which the sandstones contained little or no oil during the formation of the original oil-water contact and no residual oil has been found beneath the contact.

The second section is aligned northwest-southeast between sections 26-12-12 and 07-10-14. In this area the contact migrated vertically through the sandstones to the present location and only the upper portions of the water legs contains residual oil.

In the third area the oil-water contact has moved upward from the base of the sandstones to the present oil-water contact, with residual oils occurring between these contacts.

To the east and north of the third area the fourth section is defined as those sandstones that have contained hydrocarbons since emplacement.

Determining when the original oil-water contact formed was attempted using restored sections. These sections are diagrammatically illustrated in figure 18. Near the end of the Cretaceous the contact was nearly horizontal since it parallels the shallowest correlatable coal. Also the study seems to indicate no spillage of oil into the Eileen structures during Cretaceous times, but farther eastward tilting of the structures eventually caused migration into this area.

It has been posulated that no oil has been discovered in the Colville structure because the Jurassic strata separate the Cretaceous source rocks from the Permo-Triassic reservoirs. Another reason for the lack of hydrocarbons in the western structure is that during the time of oil migration it was much deeper than the Prudhoe structure.

Continued easterly tilting has placed the Prudhoe structure deeper than the Colville structure yet the interupting syncline and its associated faults probably restrict the migration of oil into the Colville structure. The Eileen structures appear to have received the only spillage. On the other hand, the Colville structure may have had oil spilled into and through it. This hypothesis is supported by the show of oil in the Ivishak Sandstone in the Colville No. 1.

IX. DISTRIBUTION OF HYDROCARBONS

In the Main area of the field the gas-oil contact in the Ivishak Sandstone is a -8,578 ft. (-2, 615 m). The contact is deeper in the Eileen area and averages -8,780 ft. (-2,676 m). The Ivishak Sandstone reservoir contains oil that varies vertically and probably areally. Available samples indicate a gravity range from less than 15° API, near the base of the column, to 28° API at the gas-oil contact and an average of 26.8° API. This change in gravity with depth is illustrated in figure 19.

The oil accumulation and underlying aquifer contact deepends northeastward and eastward from approximately -8,925 ft. (-2,270 m) in the western Eileen area to elevations between -8,990 - -9,060 ft. (-2,740 - 2,761m) in the Main area. The contact, within the Main area, is deepest along a line that trends northwest-southeast. This line generally follows a zone of heavier oil at the base of the column where it is thickest. The Main area may contain a zone of heavier oil which is probably related to variation in the oil-water contact. It appears that these variations are not caused by faulting since contacts on opposite sides of major faults are at similar depths. The variation in elevations of the oil-water contact may be a result of lithologic and hydrodynamic effects.

At the base of the oil column an interval of dense oil has been discovered in cores that contain darker and slightly higher residual oil saturations. The maximum thickness of this heavy-oil interval measures 70 ft. (21 m) and is found where the base of the oil column is taken as the oil-water interface. This heavy-oil zone is only found in the Main field and has not been located in the Eileen area.

Oils from the heavy-oil zone have higher asphaltene contents than oils from higher in the column (fig. 20). The asphaltene content ranges from 13 to 36 weight percent compared to 1 to 5 weight percent for those oils extracted from higher in the oil column. This heavy-oil zone may have formed through a process that precipitated some of the asphaltene content of the oil with gravity segregation causing it to accumulate at the base of the oil column. The slow increase in the depth of the reservoir may have produced gas that mixed with the oil and caused the precipitation of the asphaltenes.

The absence of a heavy-oil interval in the Eileen area may have been caused by two factors: the accumulation developed later than the Main field structures and there is a smaller and less extensive column from which the heavy-oil could precipitate.

The Ivishak Sandstone formation water had an average salinity of 18,500 ppm Nacl equivalent and 20,000 mg/l total disolved-solid content.

The temperature gradient varies from northeast to southwest. At a depth of -8,800 ft. (-2,682 m) the range is from approximately 190° F (88° C) in the northeast to 230° F (110° C) in the west. The increase in Jurassic strata in the same direction may be the cause for the gradient, with the thicker strata acting as a better insulator.

X. SUMMARY

The Prudhoe Bay field is the result of a stratigraphic and structural trap. The Ivishak Sandstone, the main reservoir, is a permeable and highly porous sequence of sandstones and conglomerates with a very good net/gross ratio. The structural dip, an unconformity, and to the north, faulting, create the closure. The source rocks occur in great volumes to the south, east, and north and also seal the reservoir. The Permo-Triassic reservoirs are not the only source of production in the Prudhoe Bay area, since other reservoirs abut these source rocks at the unconformity.

The Sadlerochit Group was initially deposited over the eroded surface of the surface of the Lisburne Group in the shallow sea. The source for the Sadlerochit sediments was to the north. As regression of this area continued, coarse sediments were deposited to the south forming a large delta. In the later stages of Sadlerochit deposition the delta was drowned and the environment became more marine during the deposition of the Shublik and Sag River Formations.

Several characteristics of the field need further study; the history of oil migration, the formation and distribution of the heavy oil zone, the tilting of the oil-water contact, and the temperature gradient within the field.

Since the discovery of the Prudhoe Bay field and the completion of the Trans-Alaskan Pipeline, production has been increased with some wells producing over 11,000 b/d to quench the enormous capacity of the pipeline.

Since the great Prudhoe Bay discovery exploration has been expanded mainly north and east of the field. The Beaufort sea is being explored extensively, along with the Sag Delta and Duck Island. Thirty miles east of Prudhoe Bay there havebeen discoveries at the mouth of the Shaviovik River. Also the Canadians are combing the Beaufort Sea and have made major discoveries at Kopanoer and Koakoak, with minor finds at Tausiut and Issungnak.

XI. APPENDIX

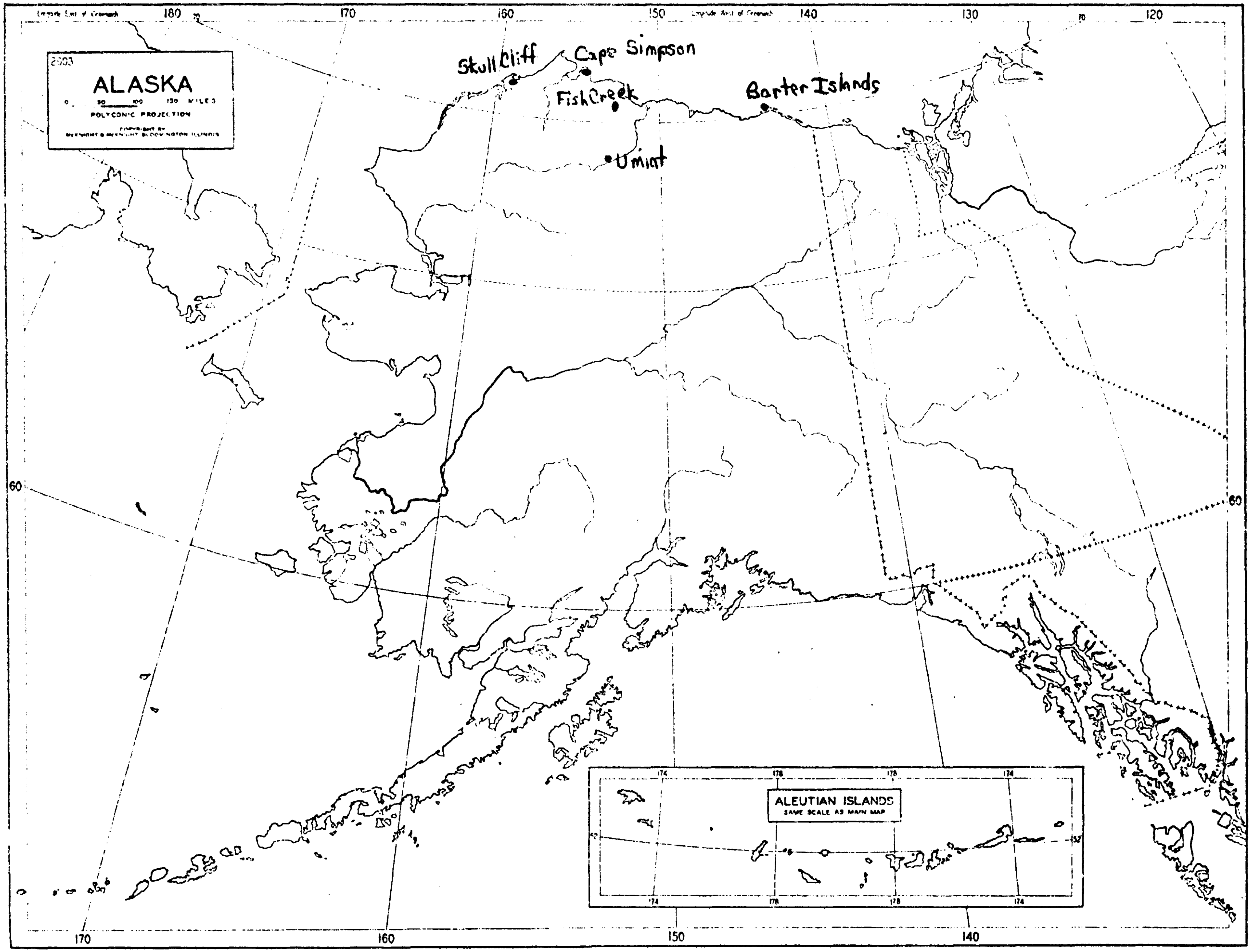


Figure 1. Location of oil seepages

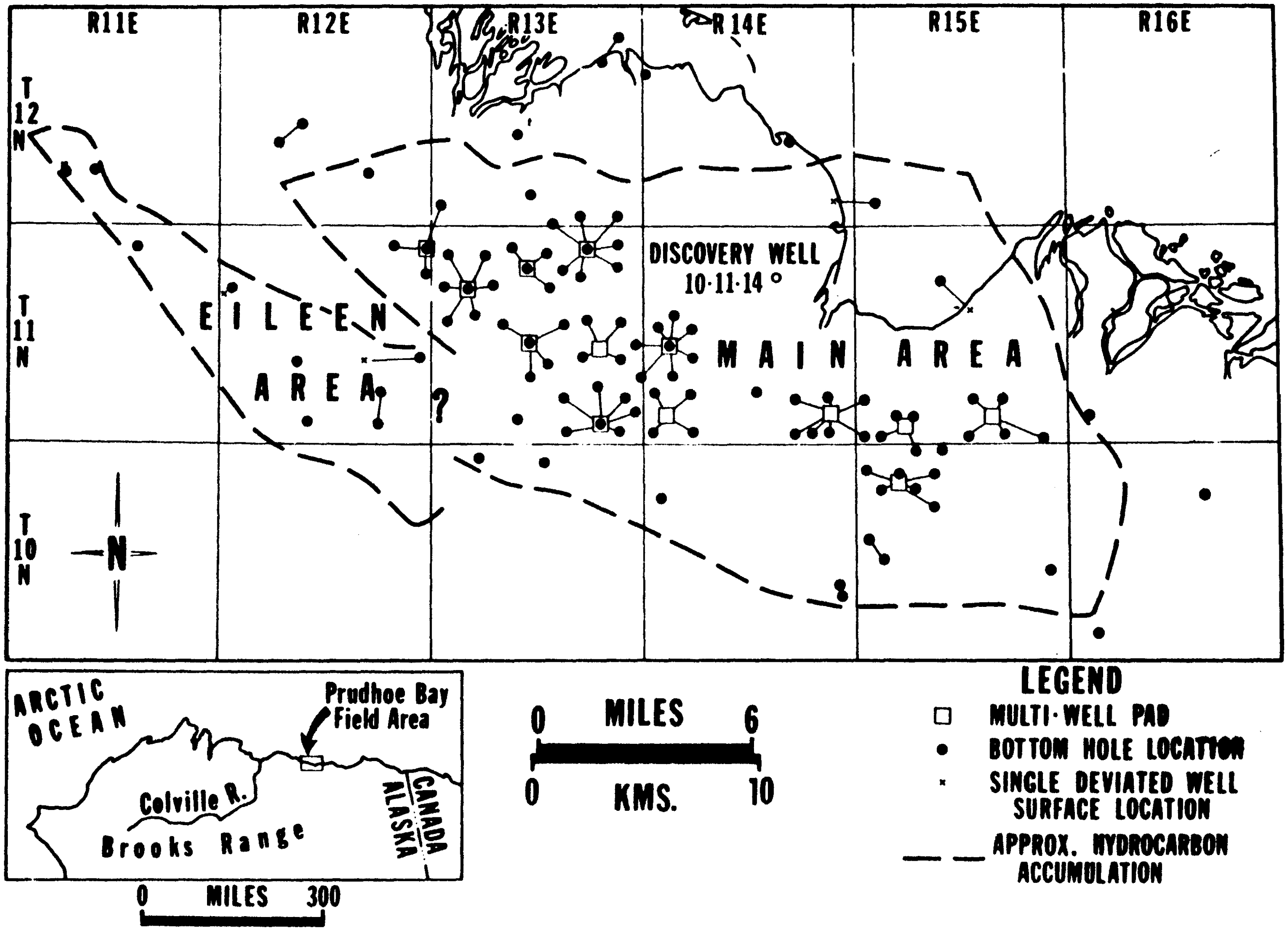


Figure 2. —Prudhoe Bay field, Alaska, location map.

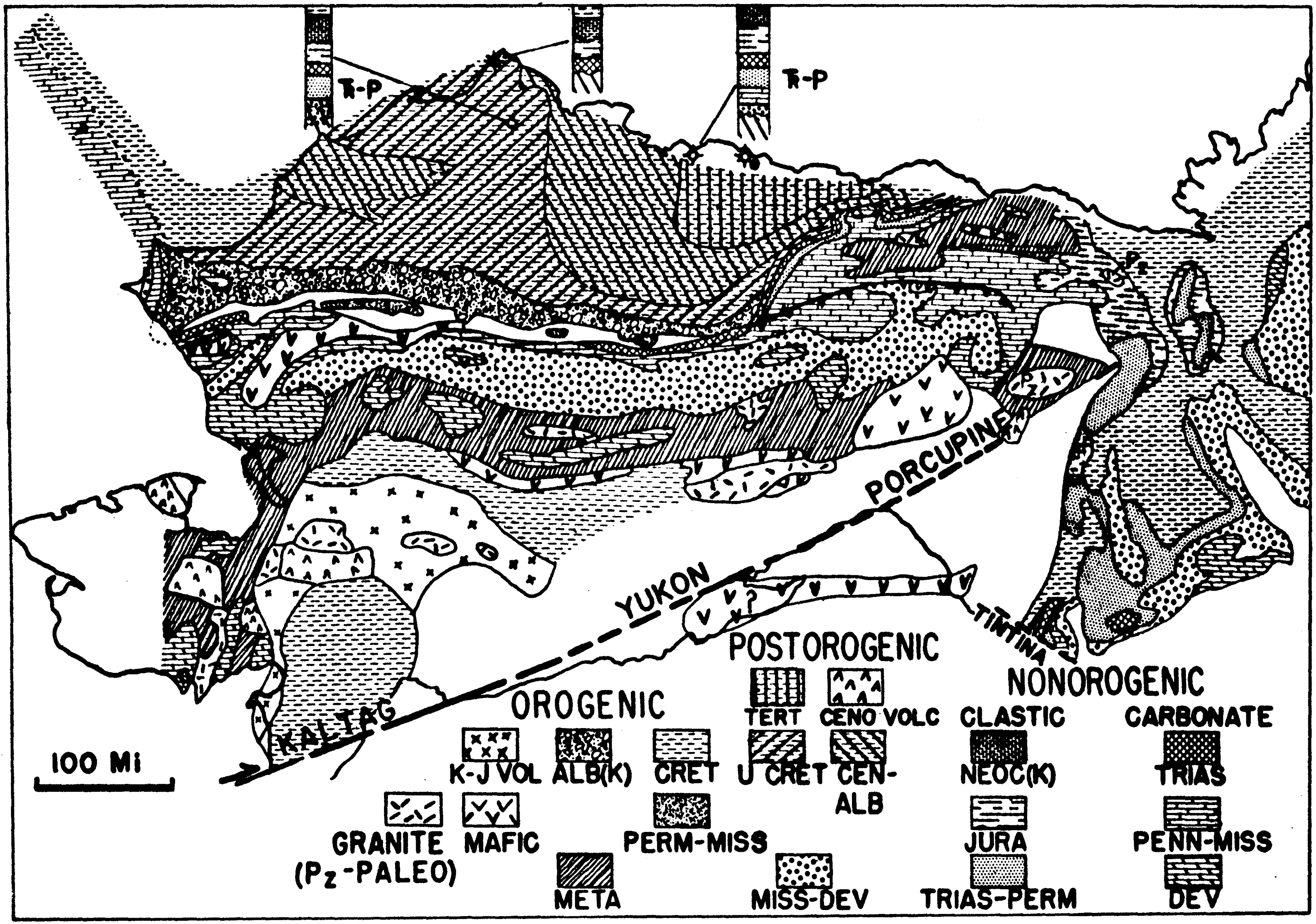


Figure 3. Regional Geology, Northern Alaska

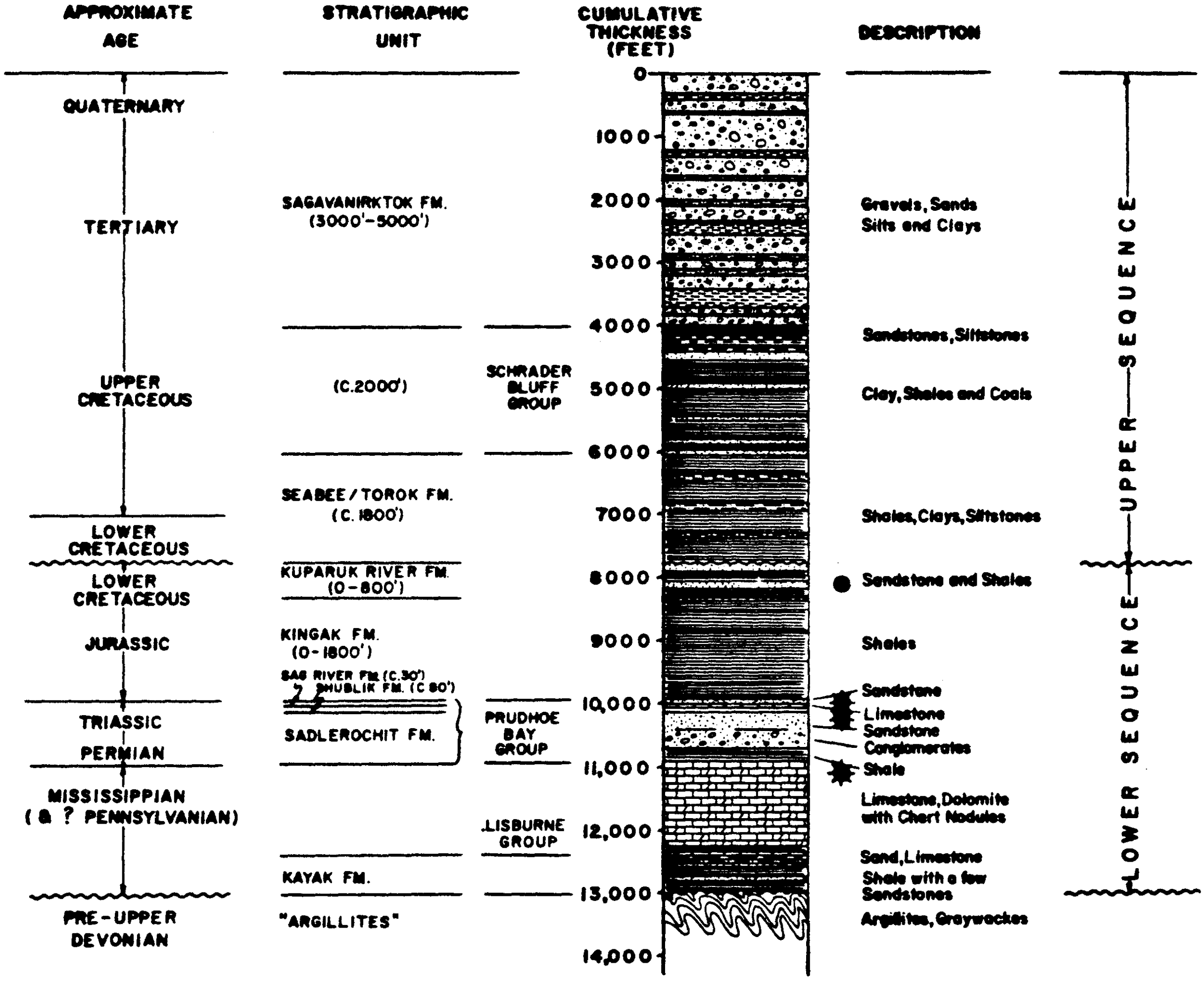


Figure 4. Generalized Stratigraphic Column of Prudhoe Bay field

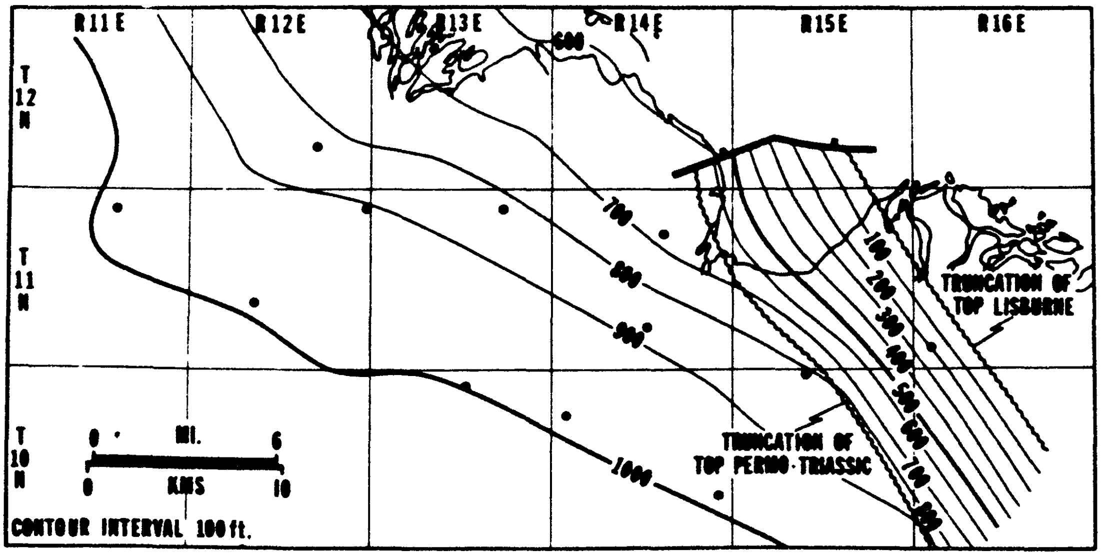


Figure 5. Thickness variation of Permo-Triassic.

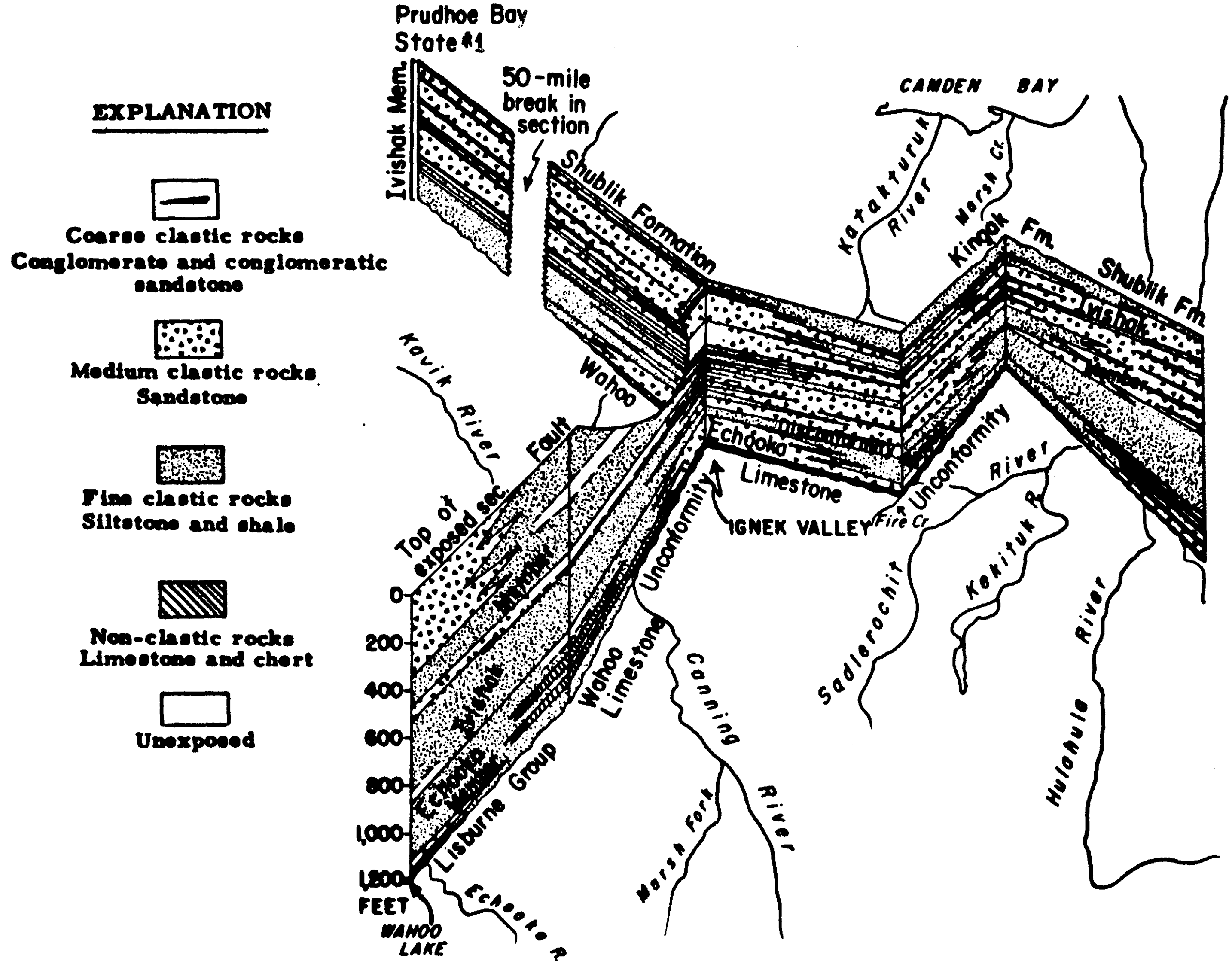
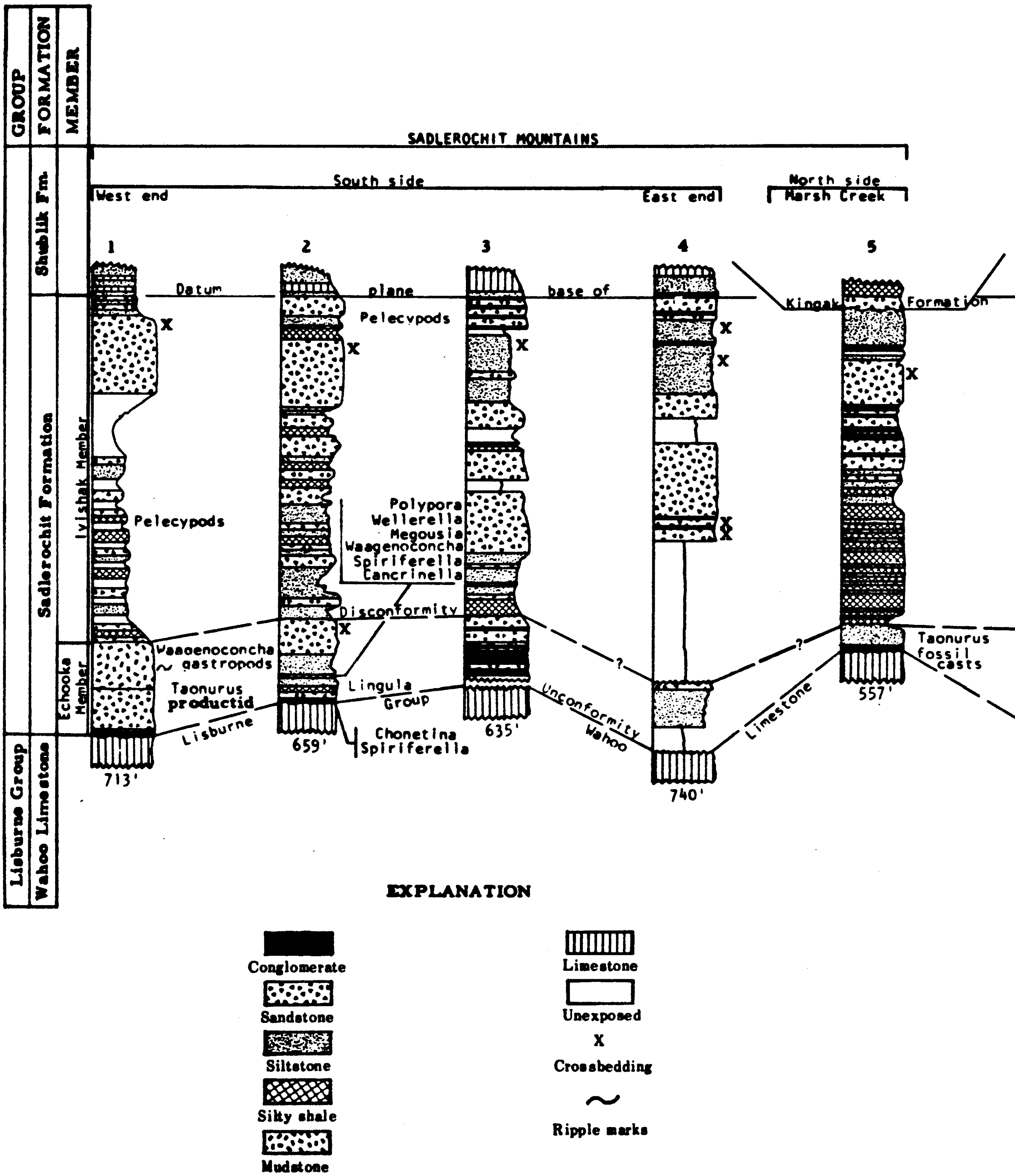


Figure 6. Cross section, illustrating Permo-Triassic


GROUP
FORMATION
MEMBER
SADLEROCHIT MOUNTAINS
South side
West end
East end
North side
Marsh Creek
Shublik Fm.
Sadlerochit Formation
Ivishak Member
Echooka Member
Lisburne Group
Wahoo Limestone
1
2
3
4
5
Datum plane base of Kingak Formation
Pelecypods
X
Polypora
Wellerella
Megousia
Waagenoconcha
Spiriferella
Cancrinella
Disconformity
Waagenoconcha
gastropods
Taonurus
productid
Lingula
Lisburne Group
Chonetina
Spiriferella
Unconformity
Wahoo Limestone
Taonurus
fossil
casts
713'
659'
635'
740'
557'
EXPLANATION
Conglomerate
Sandstone
Siltstone
Silty shale
Mudstone
Limestone
Unexposed
X
Crossbedding
Ripple marks

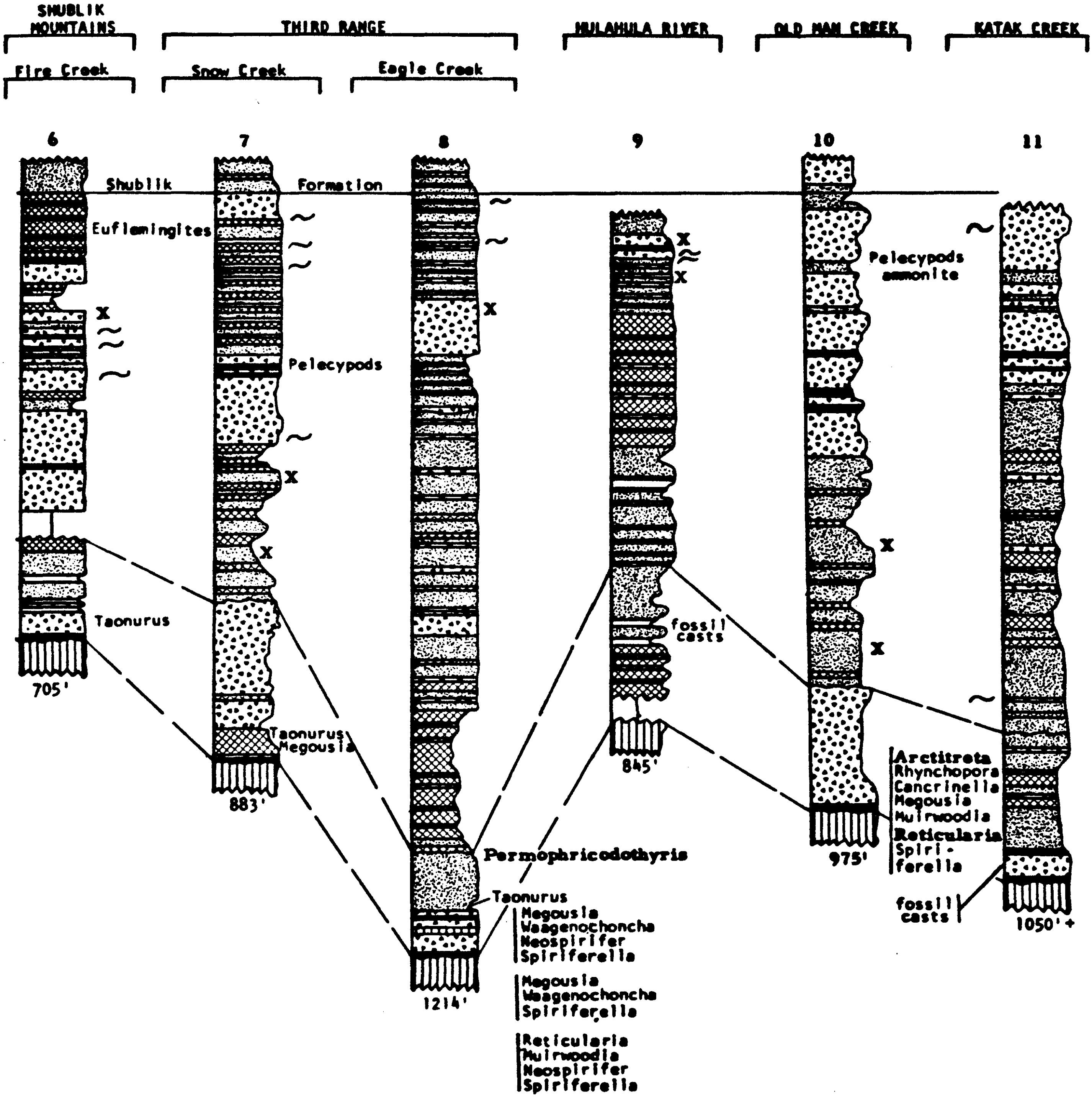


Figure 7. Measured section of the Sadlerochit Group

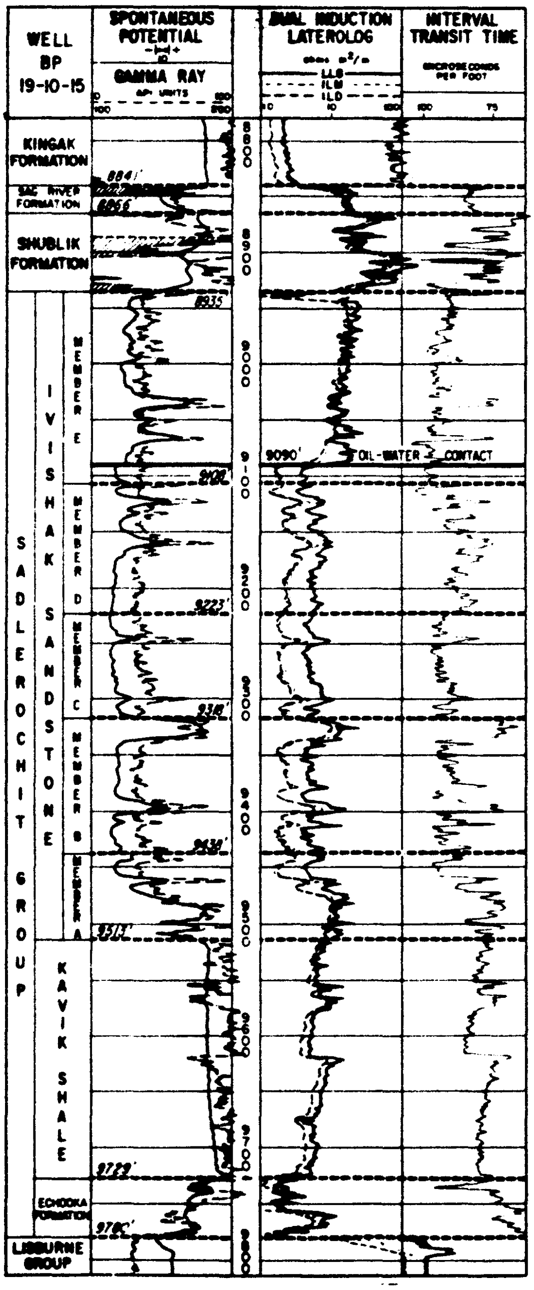


Fig.8. Permo-Triassic reference section in BP well 19-10-15.

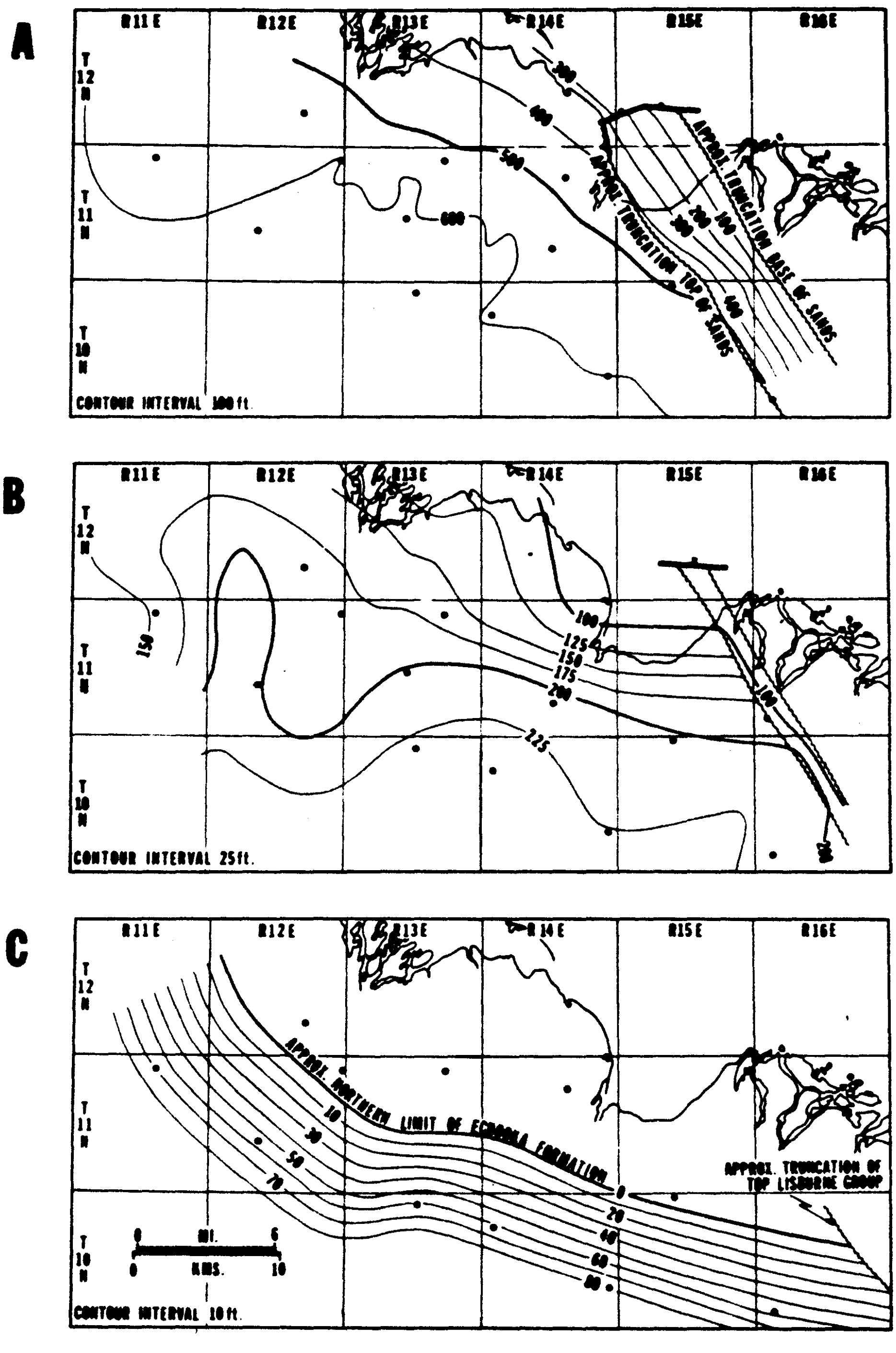
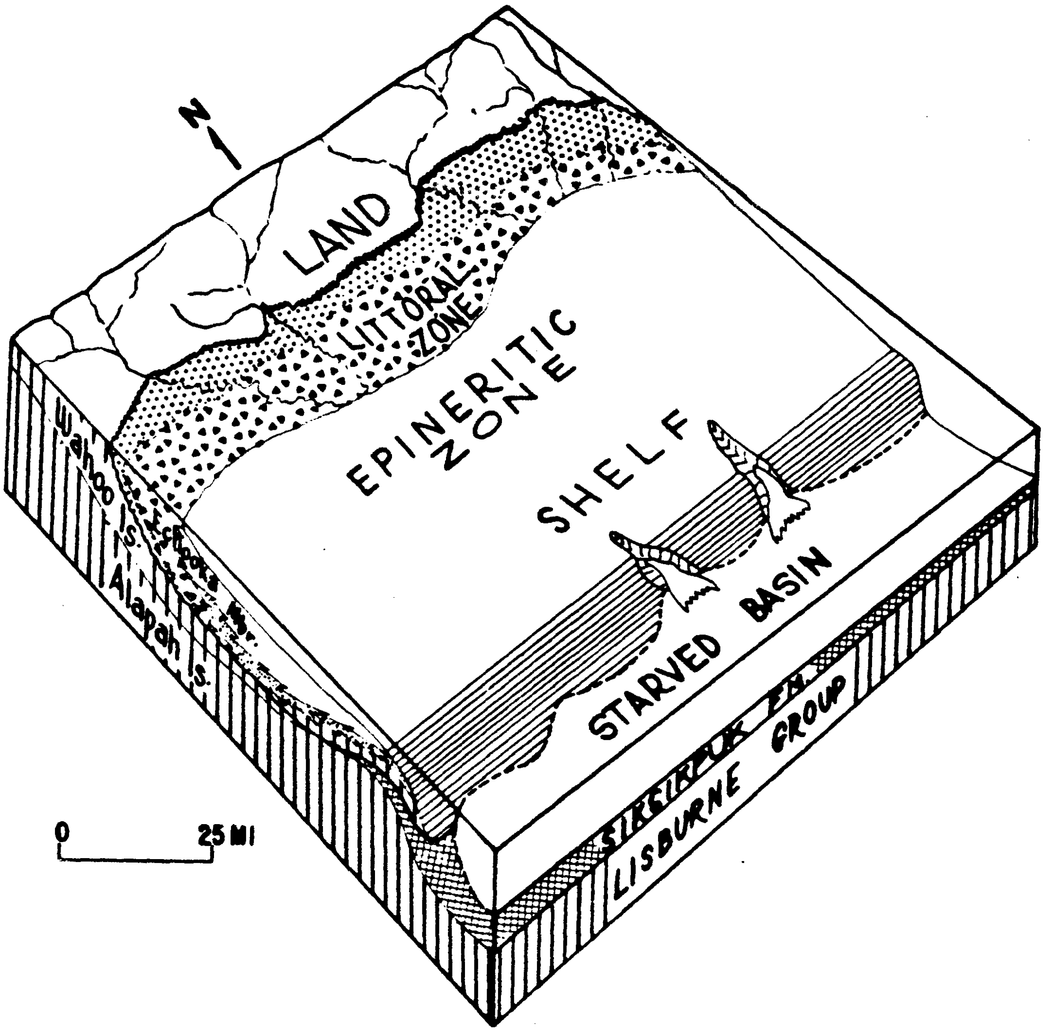


Figure 9. -Thickness variations within (A) Ivishak Sandstone, (B) Kavik Shale, (C) Echooka Formation.



EXPLANATION

Conglomerate

Sandstone

Siltstone and shale

Limestone

Chert and shale

Figure 10.Schematic diagram of the Echooka Member.

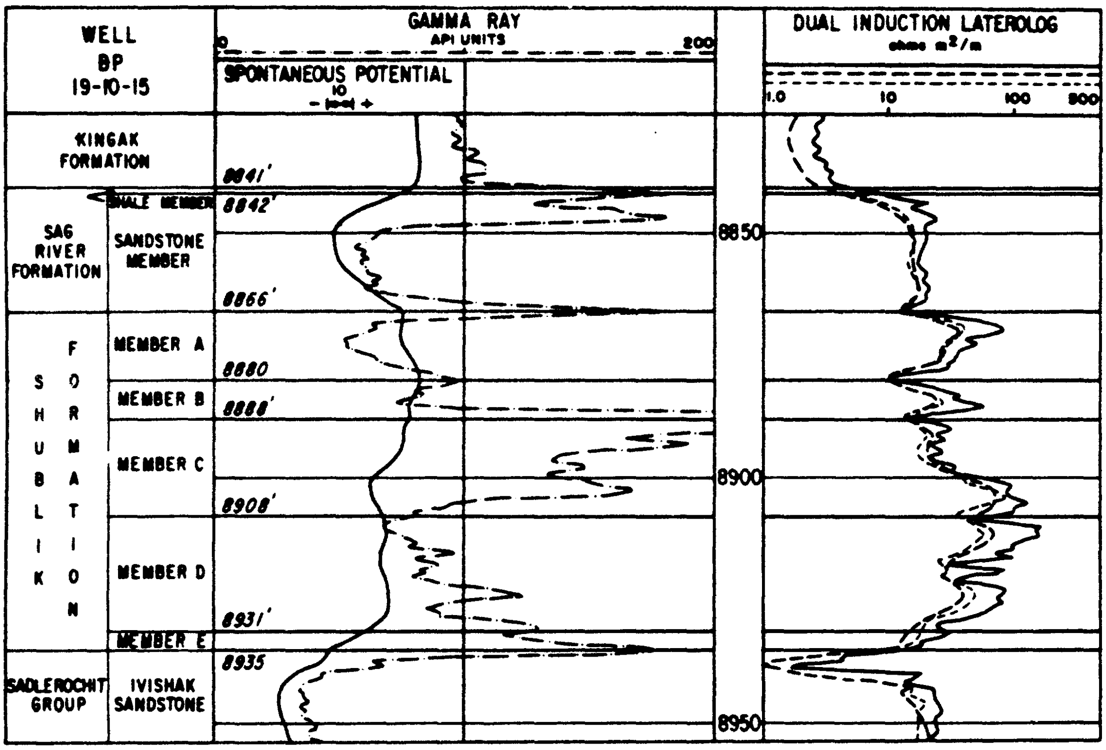


Figure 11. Subdivisions of Sag River and Shublik Formations in BP well 19-10-15.

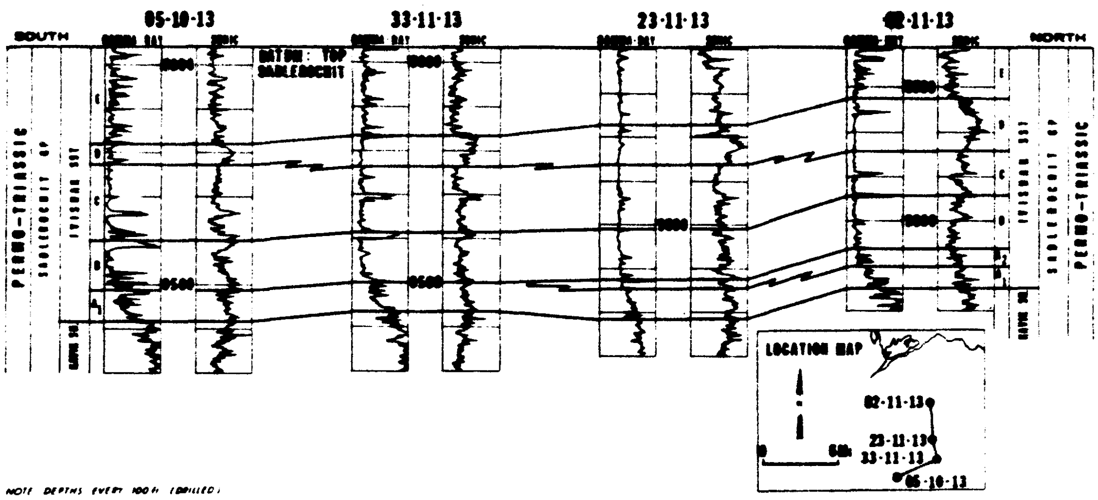


Figure 12. —South-north cross section illustrating subdivisions of Ivishak Sandstone.

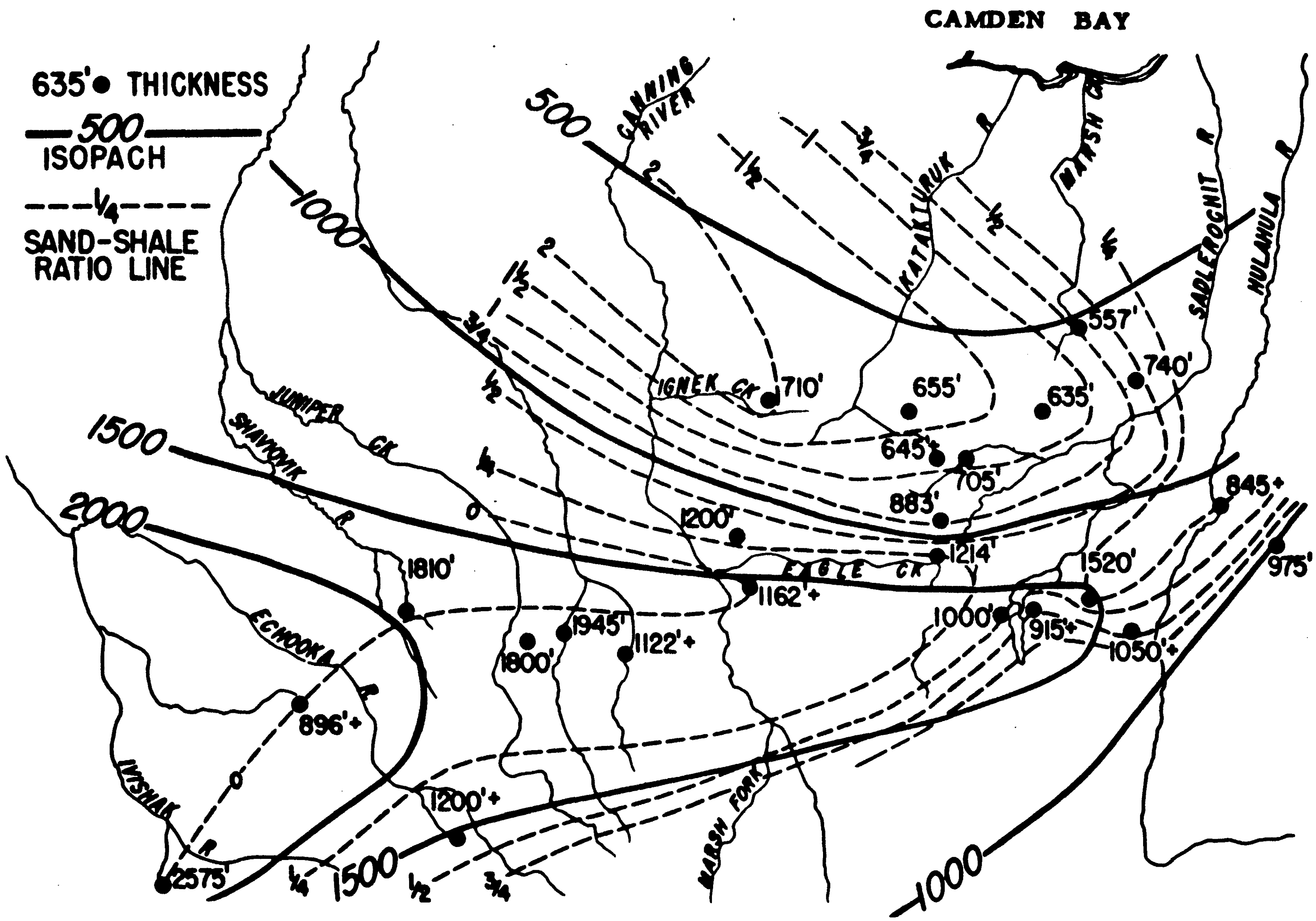


Figure 13. Isopach map of the Sadlerochit Formation showing sand--shale ratio.

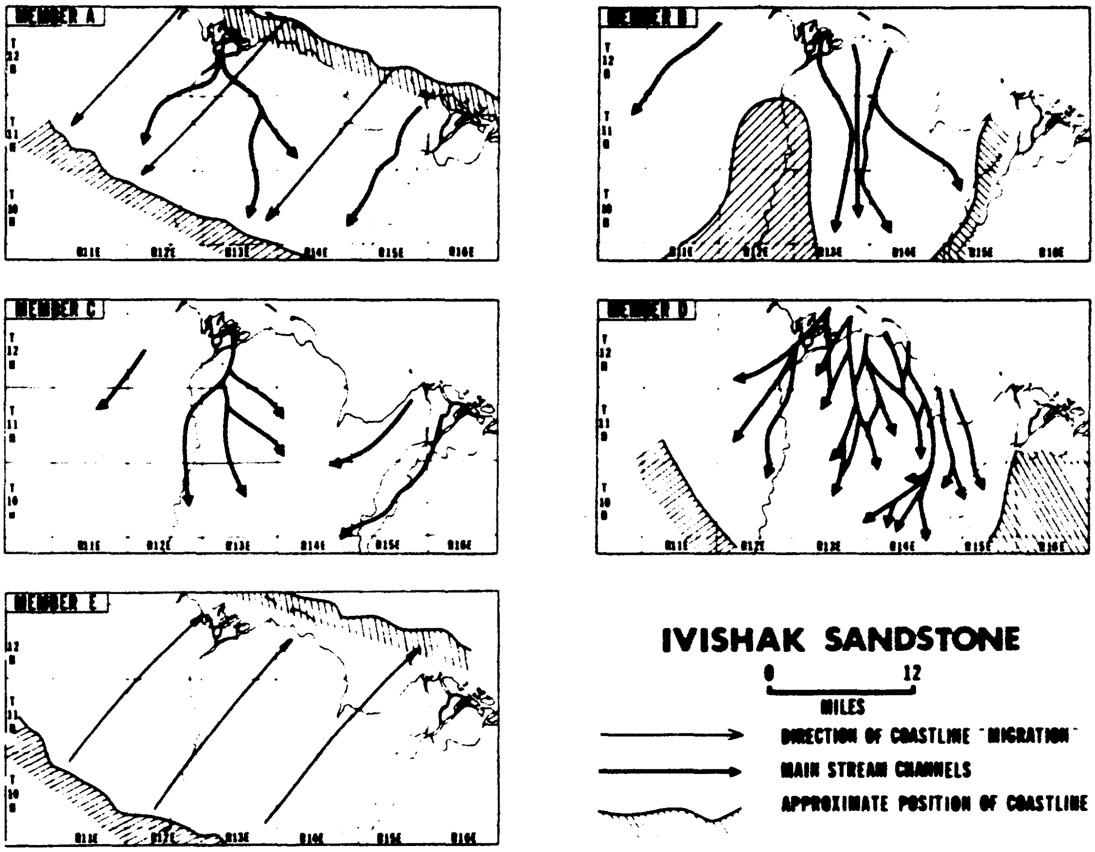


Figure 14. -Idealized paleogeography of Ivishak Sandstone.

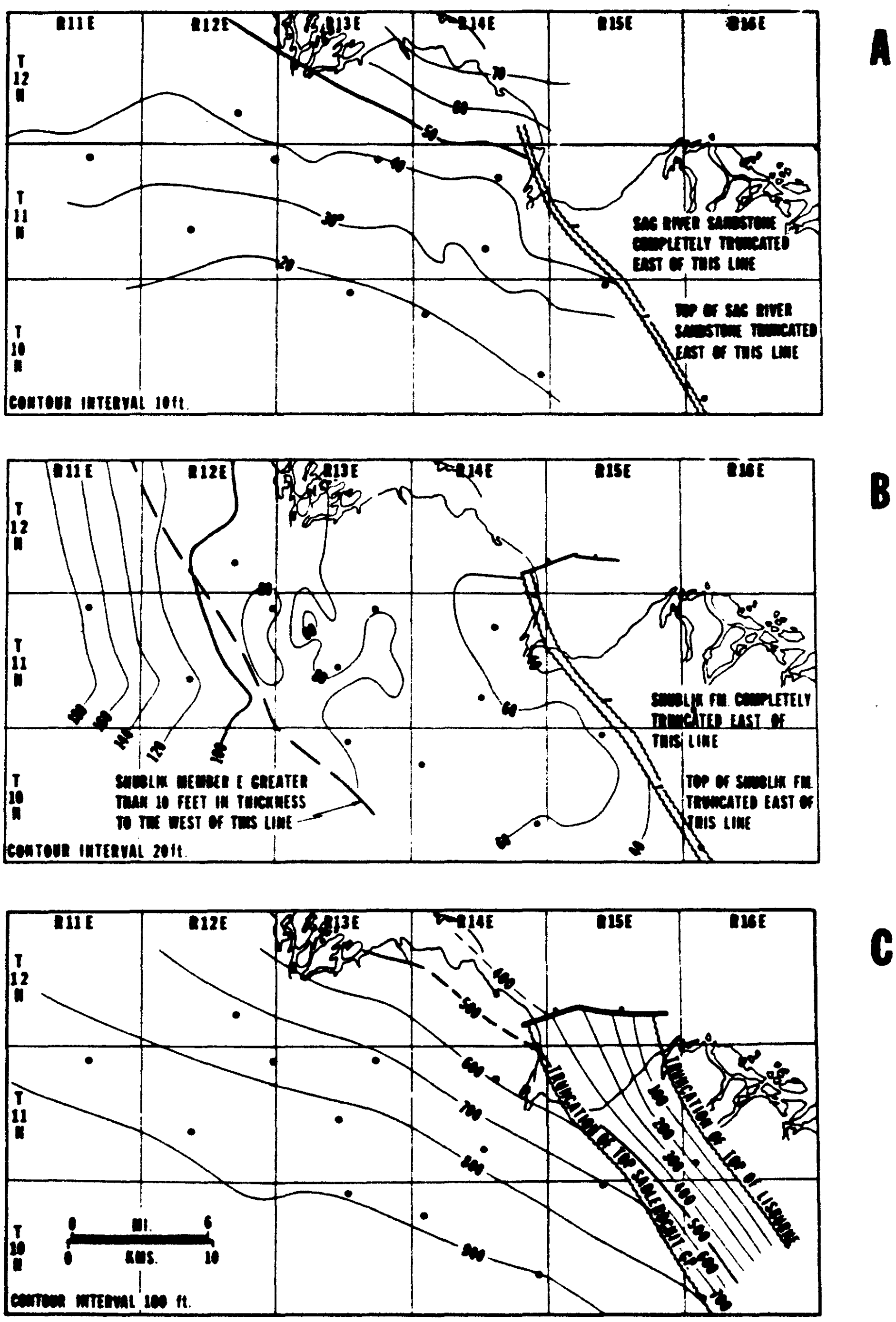


Figure 15: -Thickness variations within (A) Sag River Formation, (B) Shublik Formation, (C) Sadlerochit Group.

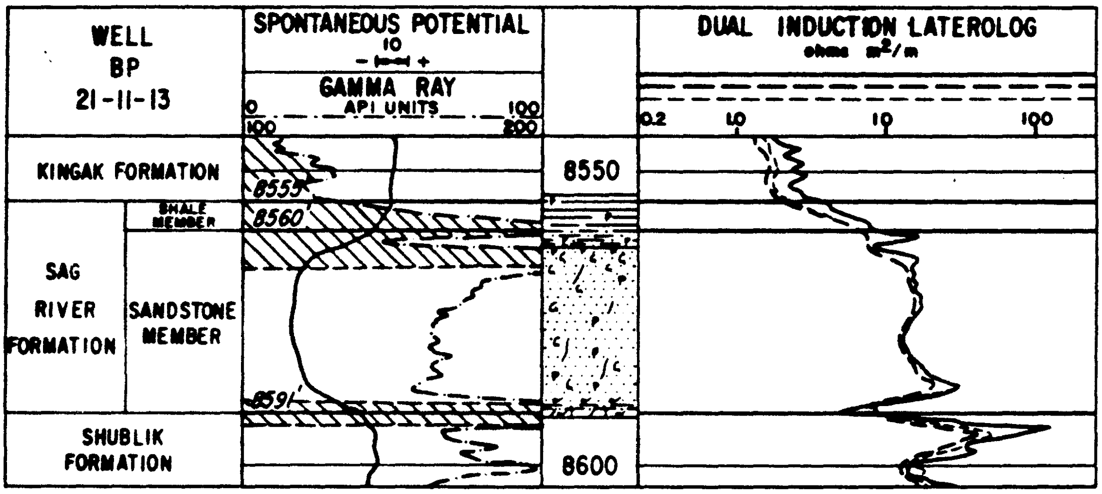


Figure 16. Sag River Formation reference section, BP well 21-11-13.

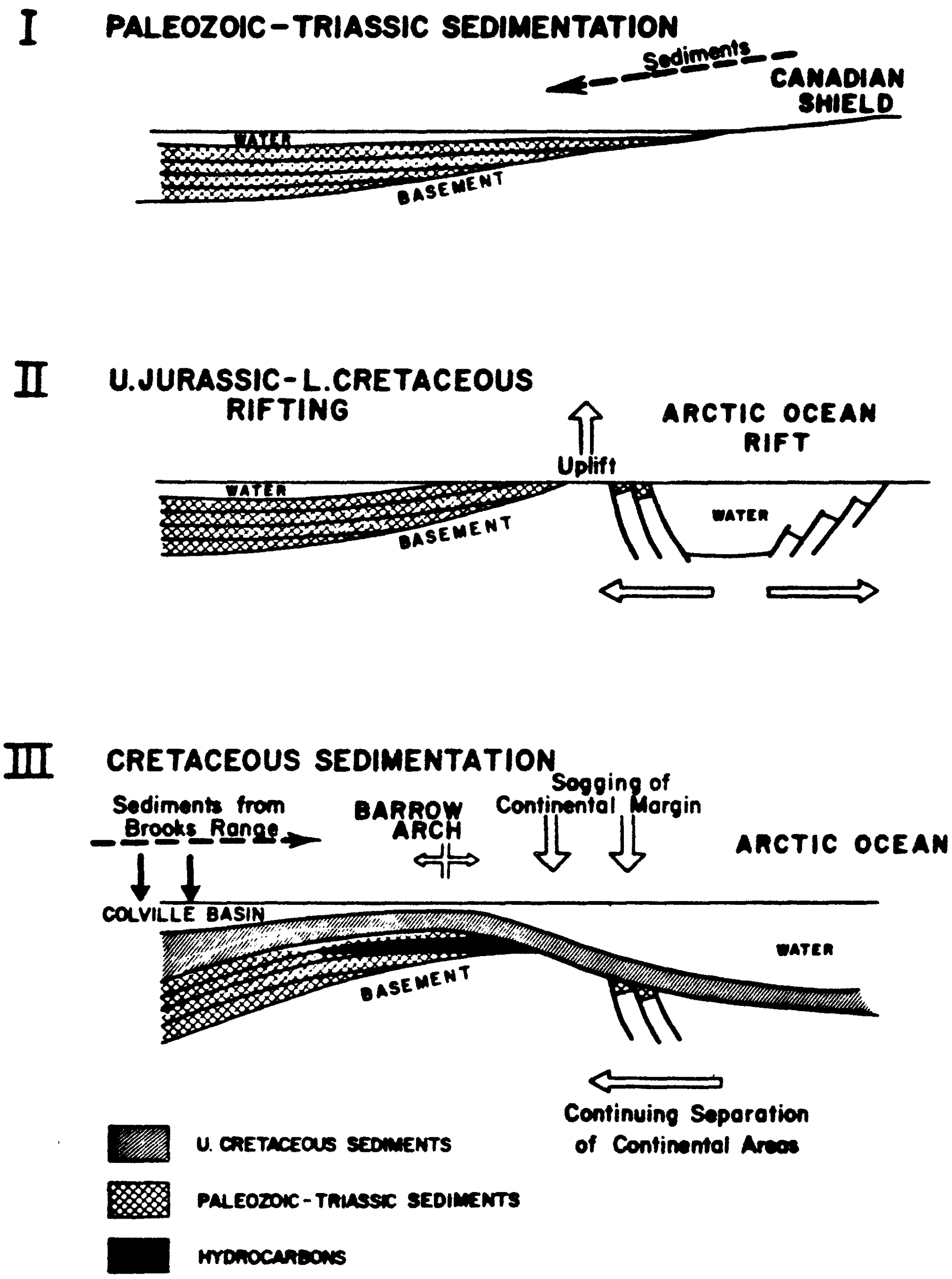


Figure 17. Diagrams illustrating the development of the northern continental margin of Alaska

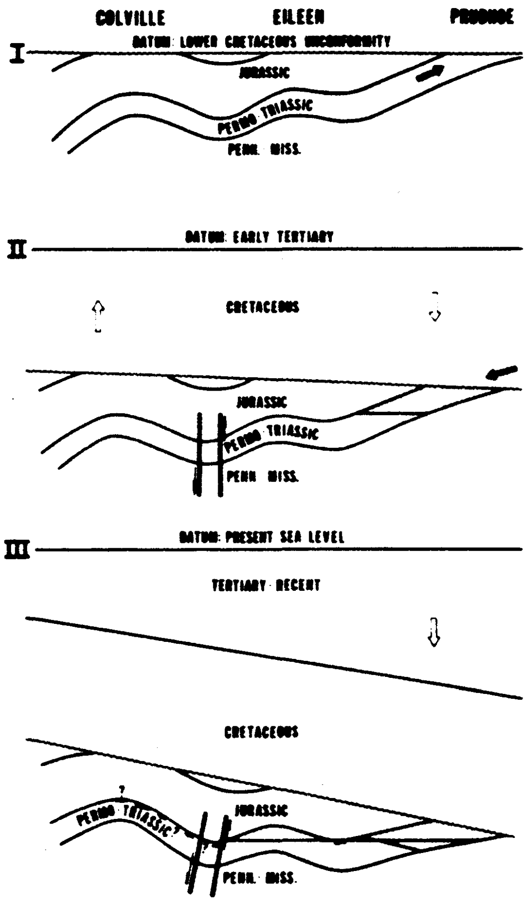


Figure 18 -**Summary of oil migration in Permo-Triassic of Prudhoe Bay.**

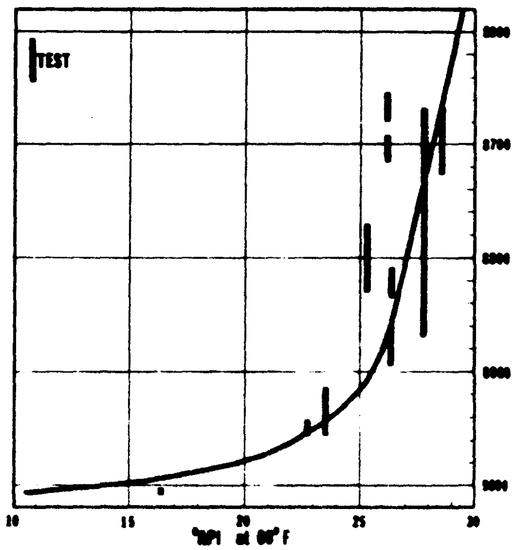


Figure 19. —Gravity-vs-depth plot, Sadlerochit crude oil.

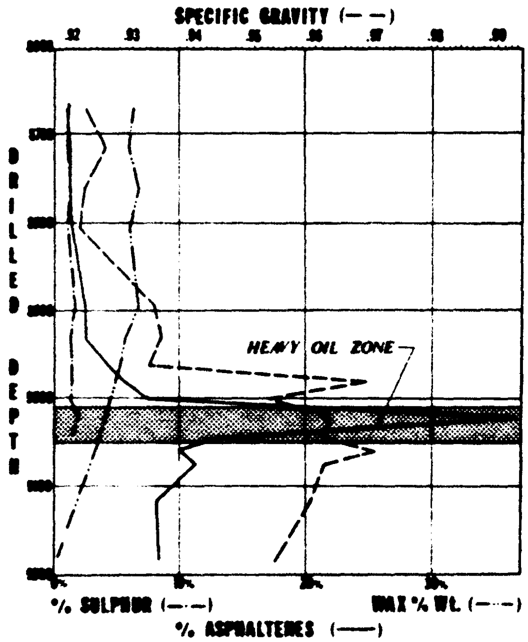


Figure 20. —Analyses of Sadlerochit crude oil extracted from cores in BP well 21-11-13.

XII. NOTES

1. Smith and Mertie, 1930, USGS Bulletin, 815.

2. For further details on the NPR-4 drilling program see:

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3. Morgridge and Smith, 1972, Geology and Discovery of Prudhoe Bay field, Eastern Artic Slope, Alaska

   see reference

4. Morgridge and Smith
   Ibid.

5. Tailleur, Irv, and Brosge; W.,P., 1970, Tectonic History of northern Alaska, in Proceedings of the Geological Seminar on the North Slope of Alaska: Pacific Sec. AAPG, P. E-1 to E-19

6. Moorgridge and Smith
   Ibid.

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Wilson, "Discoveries spur Beaufort Sea search off Canada", in <u>The Oil</u> and Gas Journal, V 79, No. 51, December 1981, p. 21.

Magoon and Claypool, "Two Oil Types on North Slope Alaska - Implication for Exploration" in <u>AAPG Bulletin</u>, V 65, No. 4, April 1981, p. 644.